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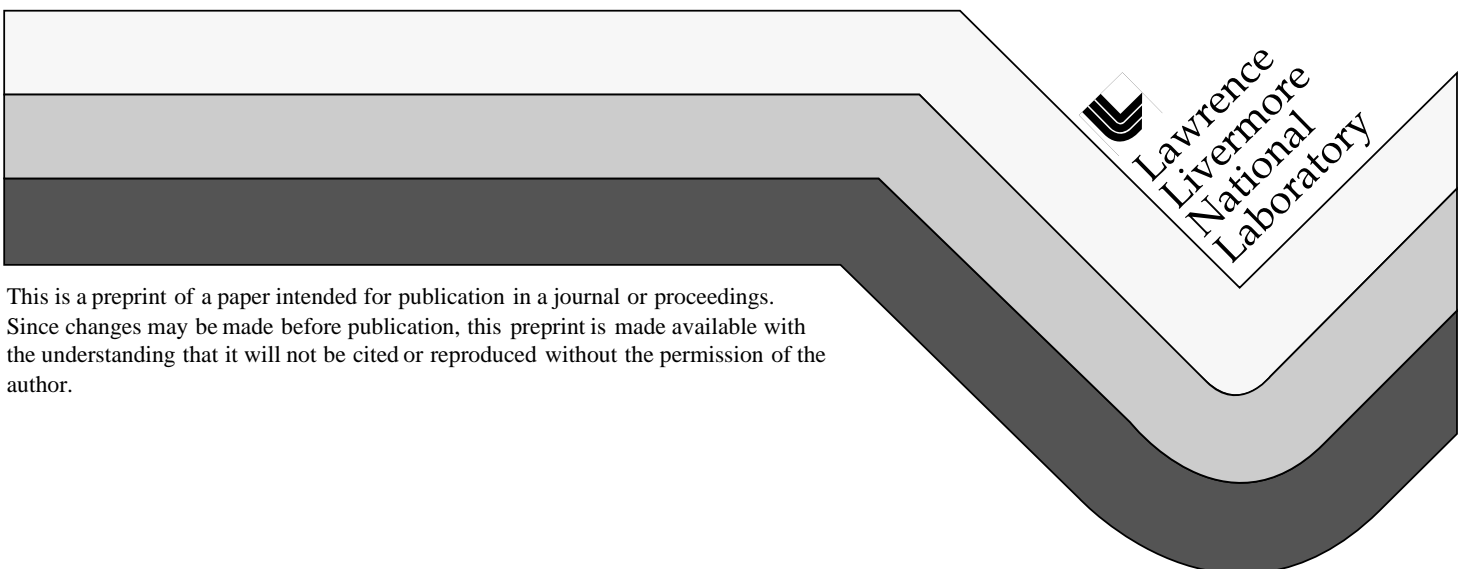
PREPRINT

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The ALE Advantage in Hypervelocity Impact Calculations

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The ALE3D code is used to model experiments relevant to hypervelocity impact lethality, carried out in the 4-5 km/s velocity range. The code is run in the Eulerian and ALE modes. Zoning in the calculations is refined beyond the level found in most lethality calculations, but still short of convergence. The level of zoning refinement that produces equivalent results in uniformly zoned Eulerian calculations and ALE ones utilizing specialized zoning, weighting and relaxation techniques is established. It takes 11 times fewer zones and about 60% as many cycles when ALE capabilities are used. Calculations are compared to experimental results.

Introduction

ALE3D is used to model experiments conducted under the Poet Lethality Analysis Team program specifically to provide benchmarking data for lethality code calculations. In the course of the calculations we study the effect of zoning, and run the code both in the Arbitrary Lagrange Eulerian (ALE) mode and the Eulerian mode. The calculations show large dependence of physical parameters such as peak pressures and the timing of peak pressures on zone size, in fact convergence is not achieved even though zone size is taken to smaller dimension than that typically found in lethality calculations. Comparison of the calculations run in the two modes with each other, and with the experimental data allow us to establish the number of zones required to produce similar numbers in the ALE and Eulerian modes of running ALE3D.

Experiments

In the experiments a spherical aluminum 2.54cm diameter projectile impacts a water filled steel cylinder, surrounded by the three more water filled cylinders and two solid aluminum ones. The cylinders are ~20 cm long ~6 cm in diameter with ~0.6cm walls, and are instrumented with gages that respond to pressure. An artist's view of the experimental setup is given in Figure 1. The cylinders are designed to fail at the waist before the ends, one of which has gage feedthroughs, give way. The gages are carbon-composition resistors encased in thin brass tubes. We model two nominally identical experiments that produced data. A preliminary report describing the experimental conditions and data has been published¹. The two tests, referred to as 9714 and 9715 had nearly identical projectile velocities of 4.09 and 4.03 km/sec respectively. The nominal aimpoint was right at the center of the cylinder close to the midplane which contains a pressure gage. The actual hit points were both 0.76cm to the side of aimpoint, at aimpoint height for 9715 and 1.65cm low for 9714. Both tests broke open the impacted cylinder, flattened the one directly behind it without opening it and opened a small gash in the cylinder adjacent to the impacted one located to the right of it. Pressure profiles were measured in both adjacent and rear cylinders. Early pressures were measured in the impacted cylinder shortly followed by gage failure. No meaningful pressures were measured in the diagonally located water filled cylinder, they were too low. The reliability of the measured pressure profiles is limited by the lack of actual gage calibration. Nominally identical gages have been calibrated by a collaboration between LANL and the manufacturer.² We have used their calibration curve. It is also known^{3,4} that the gages respond more quickly to pressure increases than to pressure decreases, and are subject to baseline drift, so we restrict our attention to the early portion of the records that incorporate the first or at most the first few peaks in the data.

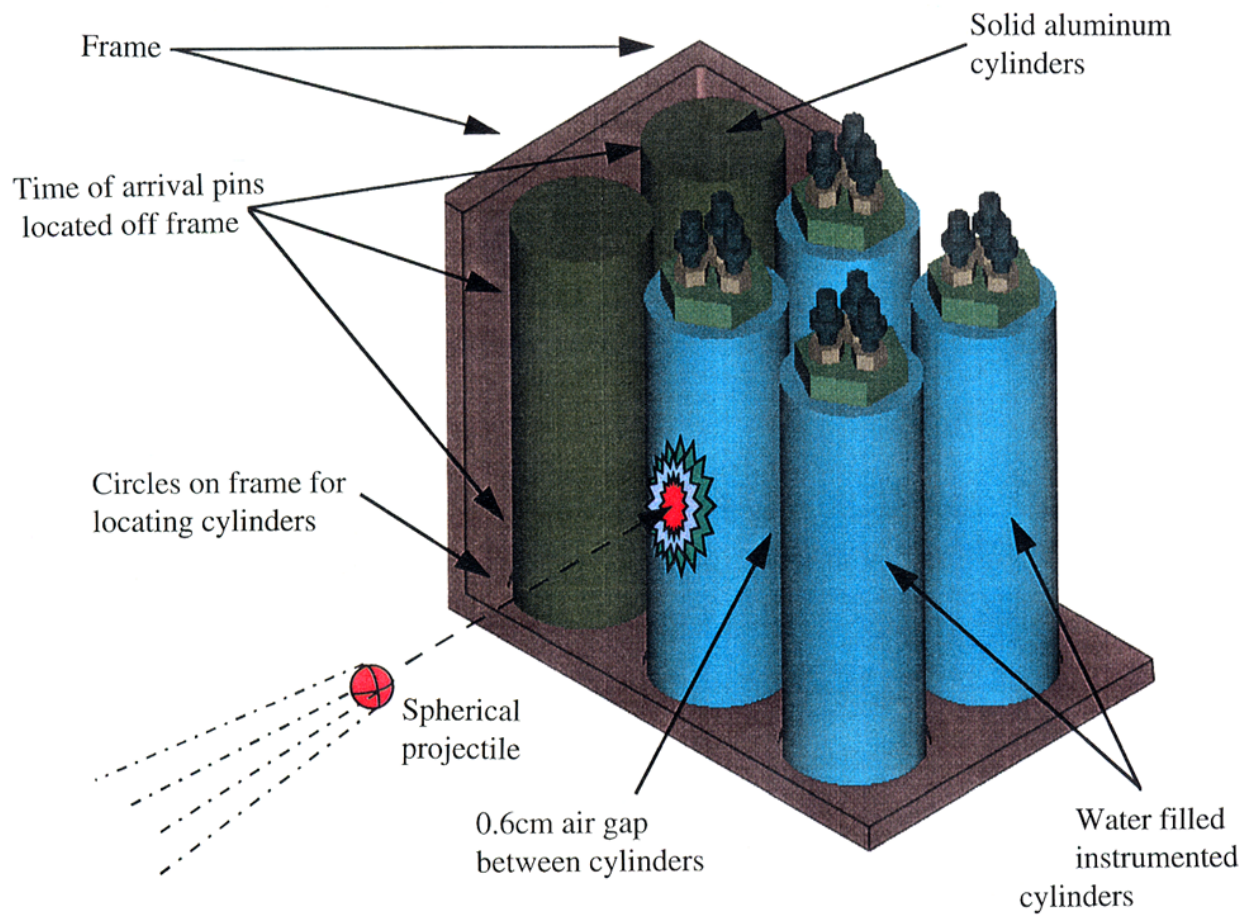


Figure 1: Artist's view of the experiments.

Calculation Method

The two experiments are modeled with one calculation. The velocity is taken to be 4.06 km/sec. A plane of symmetry is used to model only the top half of the cylinders. The below-plane impact of 9714 is approximated by moving the gage location by the same amount within the modeled portion of the cylinder (i.e. up by 1.65cm). The gage locations are shown in Figure 2. The background material is air at STP even though the experiments were carried out in an evacuated chamber. Given the small distance the projectile travels before impact in the calculations, this should have no impact. Gruneisen equations of state are used for aluminum, steel and water. A Steinberg-Guinan constitutive model is used for the metals. Failure in tension is set at 6.8kbar for aluminum and 27kbar for steel, and at an effective plastic strain of 0.2 for the cylinder walls. Water can support only 10 millibars of tension. Pressure equilibration of materials in mixed zones is turned off. Given the memory limits of the platform used in this study, we achieve the smallest possible zone size by running the calculations as two sets: one modeling the impacted and adjacent cylinders, the other modeling the impacted and rear cylinders. The two sets of calculations are fully compatible in terms of zoning, and a coarse calculation including the diagonal cylinder has been successfully run.

Impacted and Adjacent Cylinder Modeling

We start out by running ALE3D in the Eulerian mode and perform calculations with 3, 2 and 1.5mm zone size, corresponding to 2, 3 and 4 zones across the thickness for the cylinder wall. The large differences seen in the calculations prompt an additional one with 1.8mm zone sizes. Cross sections through the symmetry plane for these four different zone sizes are shown in Figures 3, 4 and 5. The starting point of the calculation is shown in Figure 3, while the other two figures show the calculation 20 and 40 μ sec later. Examination of Figures 4 and 5 shows the area gouged out in the adjacent cylinder to be zoning dependent, in fact for the coarsest zoning of 3mm the adjacent cylinder is not yet broken open (it is broken open at 60 μ sec into the calculation). The calculated pressure profiles for the four different zone sizes at the gage locations for shots 9714 and 9715 are shown in Figure 6. The calculated pressure profiles are quite sensitive to zone size. For 3mm zone size there is no discernable peak in either profile. The profiles get more peaked as zoning is refined with a well defined peak lasting ~ 35 μ sec evident in the pressures calculated with 1.5mm zoning. The calculated peak pressure is also strongly zoning dependent. For 3mm zoning the peak pressure is about three times lower than for 1.5mm zoning. Even going from 1.8 to 1.5mm zones increases the maximum pressure by a third. The peak in the pressure profiles has not converged at the smallest zone size of our calculations: 1.5mm. Platform memory and run time considerations render finer zoning impractical for this study.

Before moving on to ALE calculations, we want to look at one reason for the great zoning sensitivity of these calculations: the projectile breakup. The plane of symmetry cross section for 1.5mm zoning is shown every 2 μ sec from the beginning of the calculation to 22 μ sec in Figures 7 through 9. Several small pieces break off the projectile, starting at 8 μ sec and continuing to 16 μ sec. It is these fragments that open up the adjacent cylinder and produce the peaked pressure profile seen in the highest resolution calculation.

We then move on to ALE calculations. We first tried a uniform mesh with material weights used to refine zoning in places of interest, such as the projectile and the cylinder walls. This provided some improvement, but we found we could do better by setting up specialized zoning. In this specialized zoning we initially put the desired number of zones across the walls of the cylinders with the zone boundaries at the wall boundaries. We then relax the mesh, using weights for each material to keep zones where we want them concentrated. A cross section along the symmetry plane before and after the relaxation process is shown in Figure 10. Since the projectile breakup is a key element in these calculations we also use weighting based on effective plastic strain to keep zoning concentrated on the projectile. We perform the ALE calculations with a much smaller total number of zones, to see how many fewer can be used to produce results comparable to those of the finely resolved Eulerian runs. We now show results obtained with an

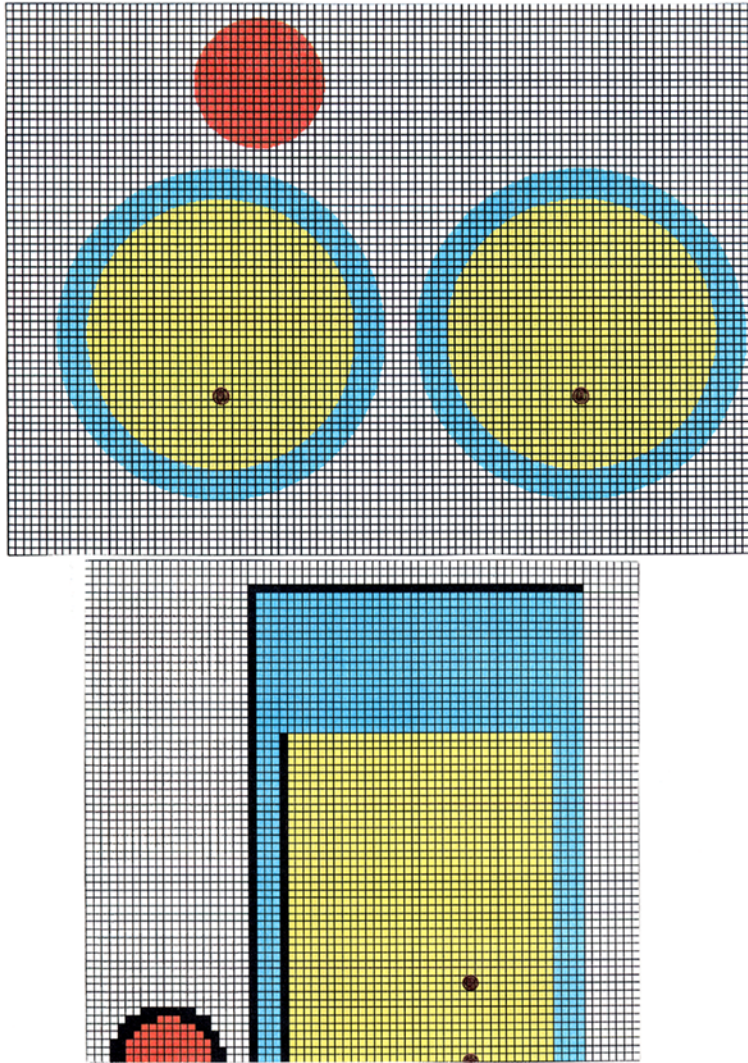


Figure 2: Cross section through the symmetry plane (top) and the plane of the aimpoint and the impacted cylinder axis (bottom) showing tracer points corresponding to gage locations in shots 9714 and 9715.

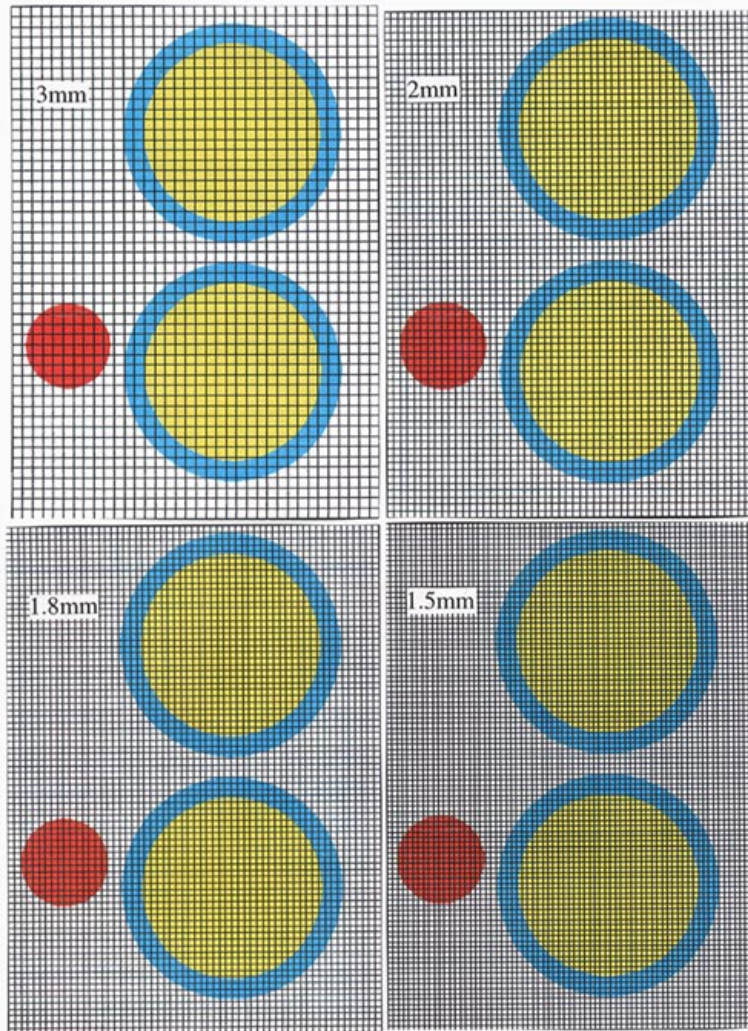


Figure 3: Symmetry plane cross sections at problem start through Eulerian runs of different uniform zoning.

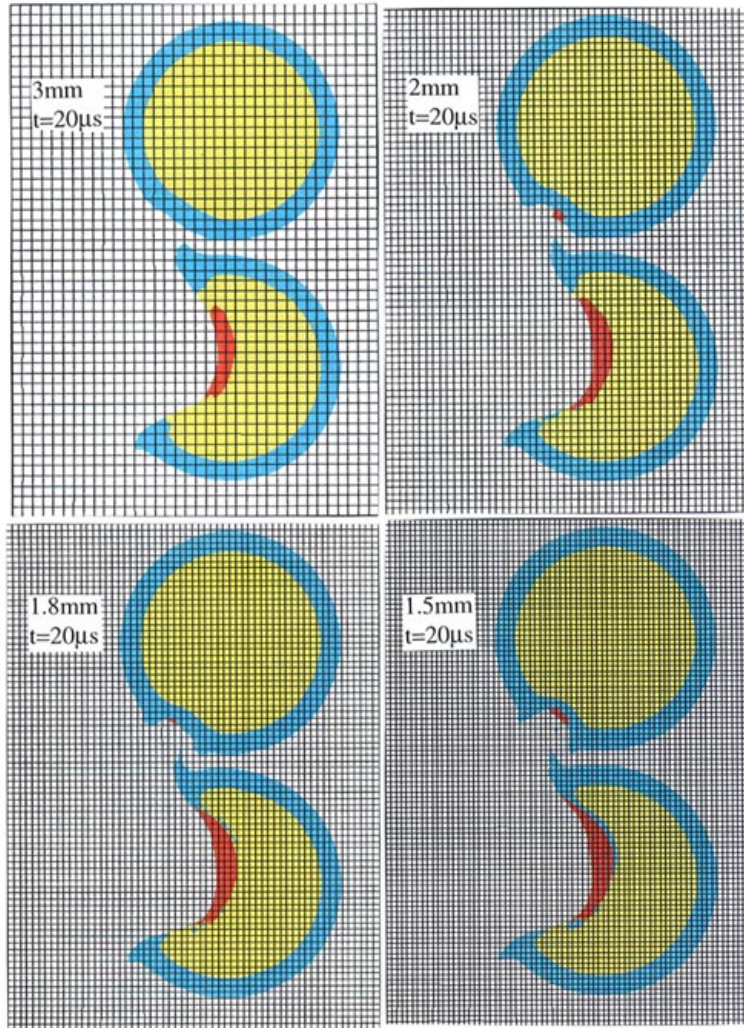


Figure 4: Symmetry plane cross section at $20 \mu s$ through Eulerian runs of different uniform zoning.

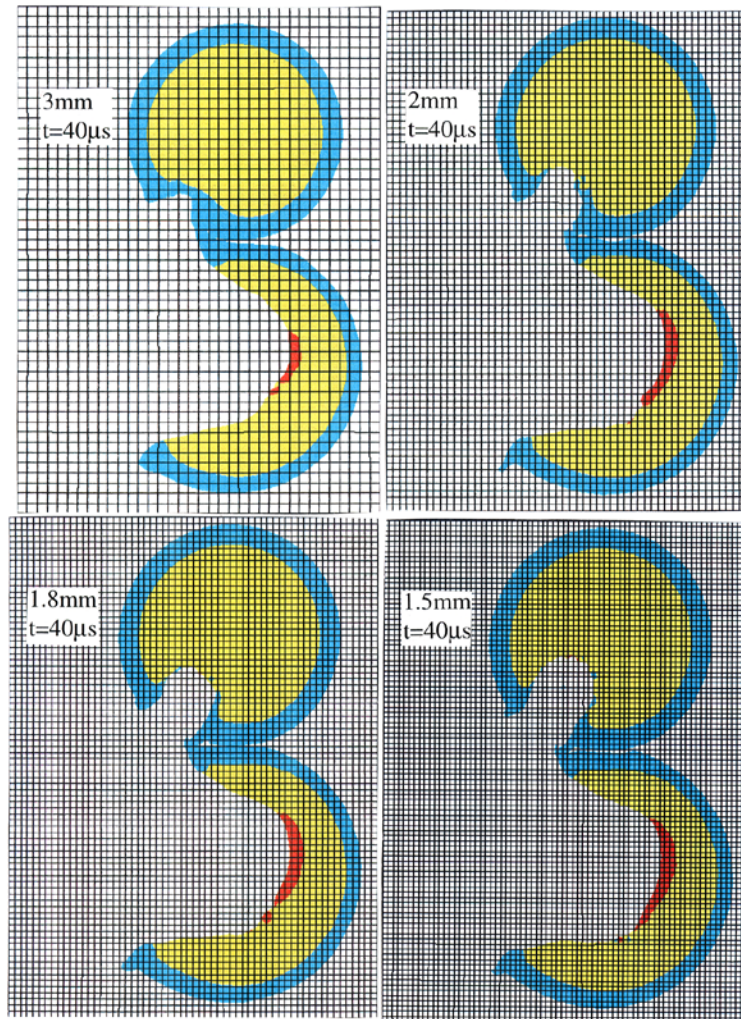


Figure 5: Symmetry plane cross sections at $40 \mu\text{sec}$ through Eulerian runs of different uniform zoning.

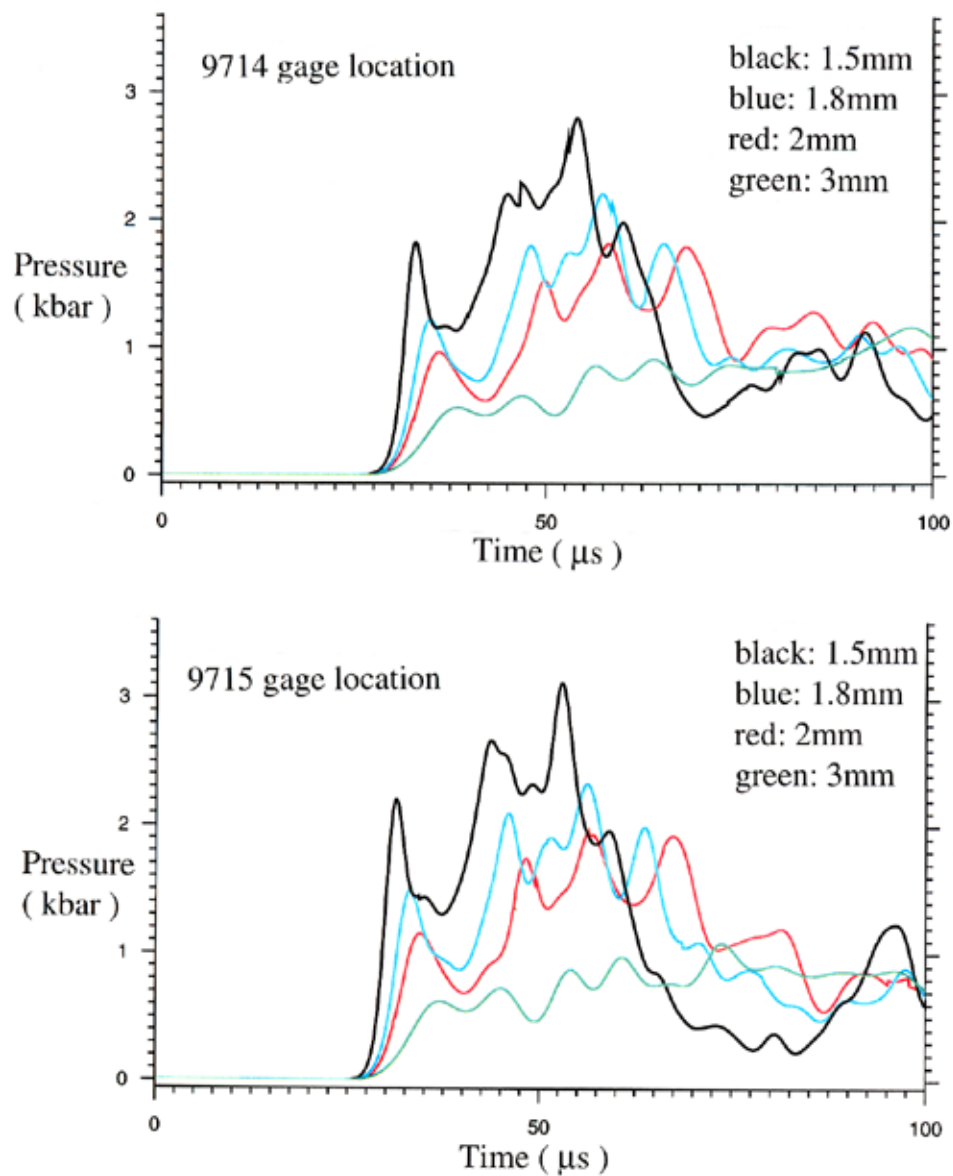


Figure 6: Calculated adjacent cylinder pressure profiles for Eulerian runs of different uniform zoning at locations corresponding to gages in shots 9714 and 9715.

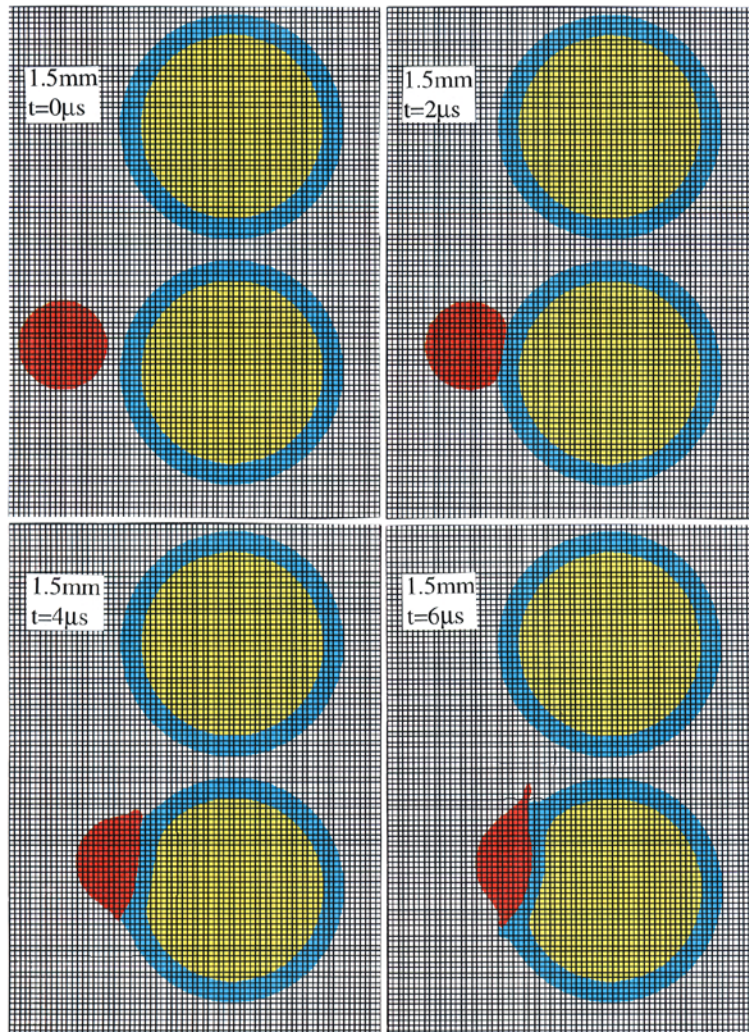


Figure 7: Symmetry plane cross section through a uniformly zoned Eulerian run showing projectile impact and deformation.

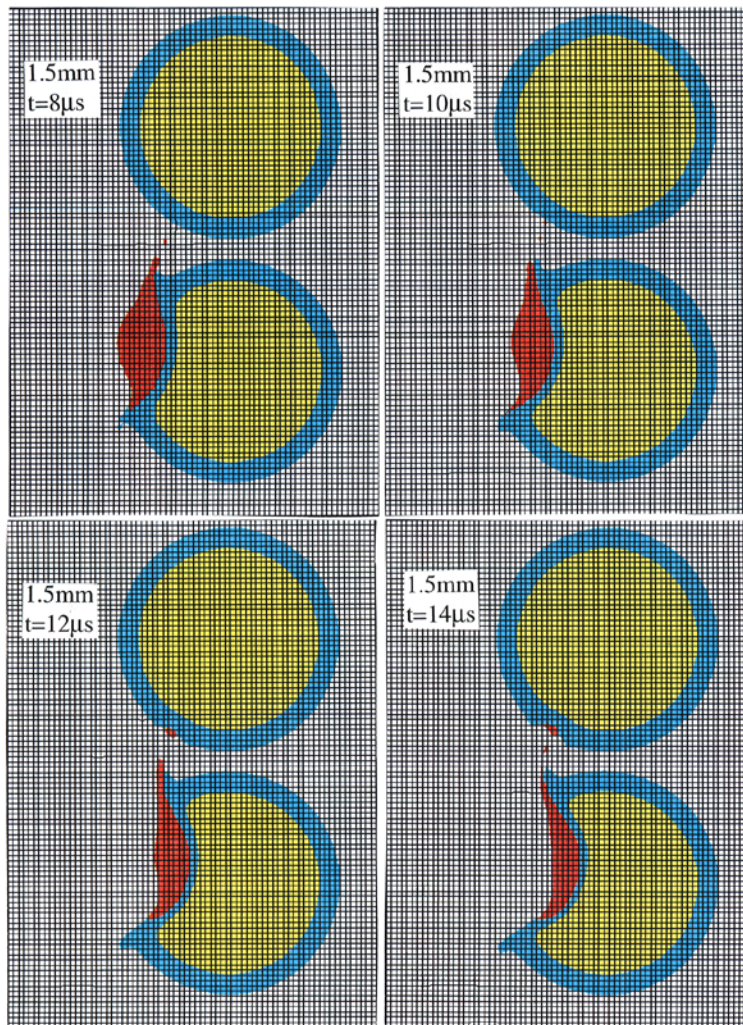


Figure 8: Symmetry plane cross section through a uniformly zoned Eulerian run showing projectile fragmentation.

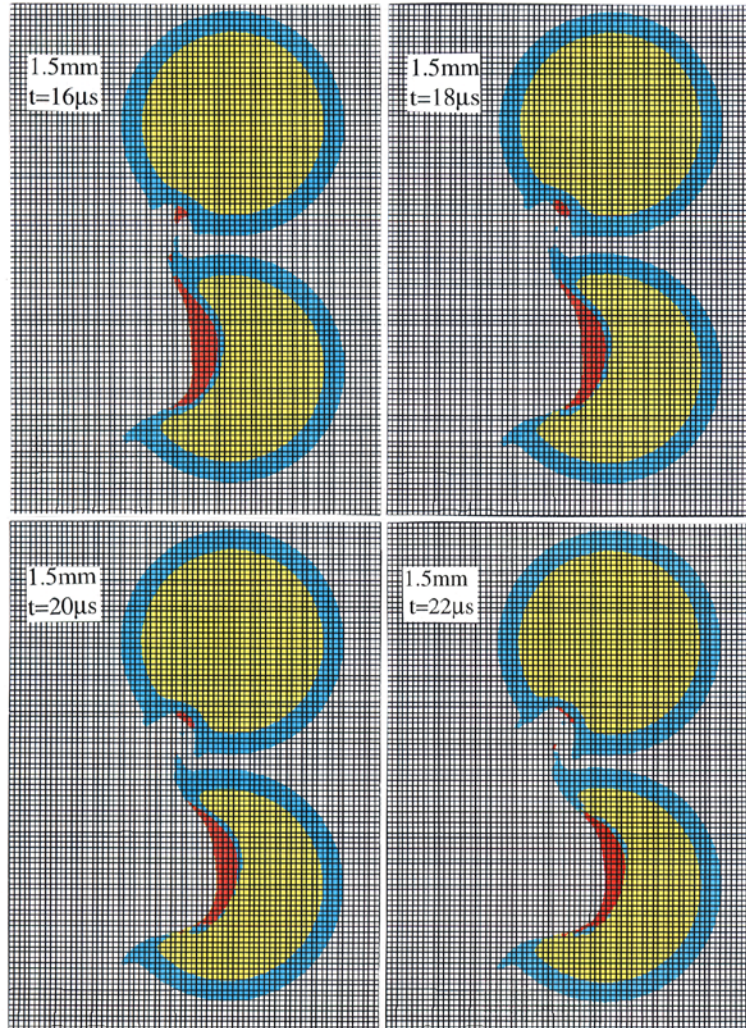


Figure 9: Symmetry plane cross section through a uniformly zoned Eulerian run showing impact of projectile fragments onto adjacent cylinder.

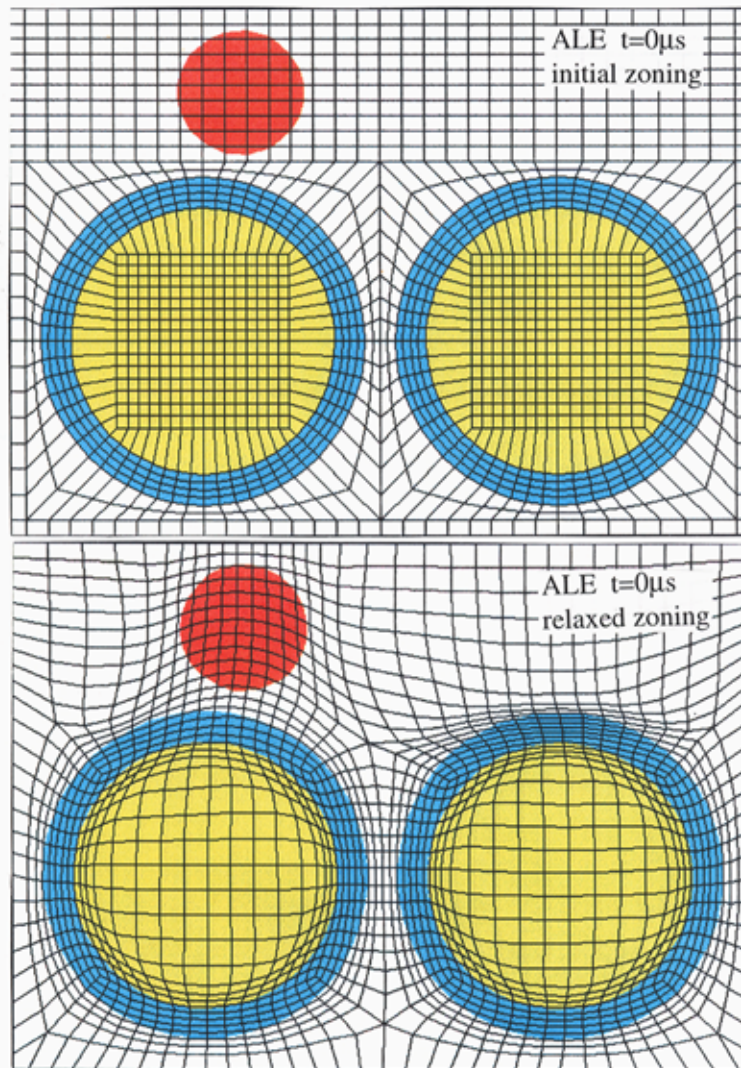


Figure 10: Symmetry plane cross section through an ALE run showing initial zoning and zoning after relaxation.

ALE calculation with 1/11 the number of zones used in the 1.5mm zoning Eulerian calculation. A plane of symmetry cross section is shown every 2 μsec from the beginning of the calculation to 22 μsec in Figures 11 through 13. The breakup is not identical to that shown earlier for the Eulerian calculation, with larger pieces coming off. Plane of symmetry cross sections at 20 and 40 μsec into the ALE and 1.5mm Eulerian calculations are shown in Figure 14. Clearly the gouging of the adjacent cylinder is comparable for the two calculations. The calculated pressure profiles at the gage locations for shots 9714 and 9715 are compared for the ALE and 1.5mm Eulerian calculations in Figure 15. The peak amplitudes are quite close, although the two profiles are not the same. The more broken-up appearance of the ALE calculated profiles is due to coarser zoning and zone boundary movement across the tracer point location.

Impacted and Rear Cylinder Modeling

Again we start out with calculations in the Eulerian mode and stop the calculations at $\sim 120 \mu\text{sec}$ when the major deformation of the rear cylinder has taken place. Cross sections through the symmetry plane for 3, 2 and 1.5mm zoning are shown in Figures 16 and 17. Figure 16 shows the starting point, while Figure 17 shows the calculation 100 μsec later. In contrast to the adjacent cylinder behavior, no large zoning dependence in the rear cylinder shape is evident. The calculated pressure profiles at the gage locations for shots 9714 and 9715 for 4, 3 and 1.5mm zoning are shown in Figure 18. We see a moderate zoning dependence in the amplitude as well as one in the timing of the first and largest peak in the pressure. Timing of the profiles as well as those from 6 and 2mm calculations are given in Table 1.

Table 1
Timing of the calculated pressure profile peaks in rear cylinder

Zone Dimension mm	9714		9715	
	First Peak Half Height μsec	Largest Peak Half Height μsec	First Peak Half Height μsec	Largest Peak Half Height μsec
6	45.5	60.5	45	60
4	55.5	71	54.5	70
3	55.5	74.5	54.5	73.5
2	58	76	57.5	74.5
1.5	59	78	58.5	77

We next perform ALE calculations with zoning and weighting conditions essentially identical to those discussed earlier for the adjacent cylinder. Since the rear cylinder is not penetrated its walls are kept Lagrangian throughout the calculation, with four zones across the wall thickness. In Figure 19 we show a symmetry plane cross section at initial time and 100 μsec for the ALE calculation, with the 100 μsec cross section through the 1.5mm Eulerian calculation included for comparison. The ALE calculation has 11 times fewer zones than the 1.5mm Eulerian calculation. The calculated pressure profiles at the gage locations for shots 9714 and 9715 are compared for the ALE and 1.5mm Eulerian calculations in Figure 20. The peak amplitudes are quite close but the timing of the first and largest peaks are even later for the ALE calculation than the Eulerian one (and later timing corresponds to finer zoning as indicated in Table 1).

Comparison of Calculations with Data

We now compare the code calculations with the data from shots 9714 and 9715. We have mentioned earlier that only manufacturer's specifications were used for translating the measured signals into pressure, that the gages are known to respond more quickly to pressure rise than to pressure fall and to exhibit baseline shifts. We also made no attempt to model the actual gage package which consists of a carbon resistor epoxied into a thin brass tube. In the calculation the

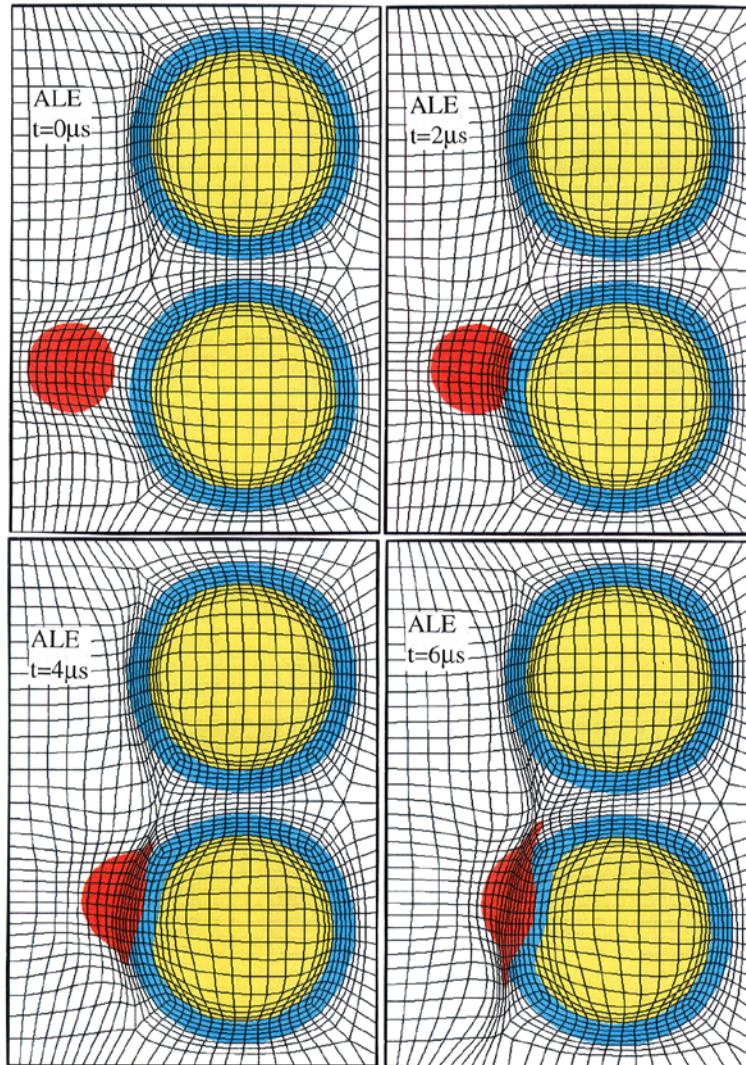


Figure 11: Symmetry plane cross section through an ALE run showing projectile impact and deformation.

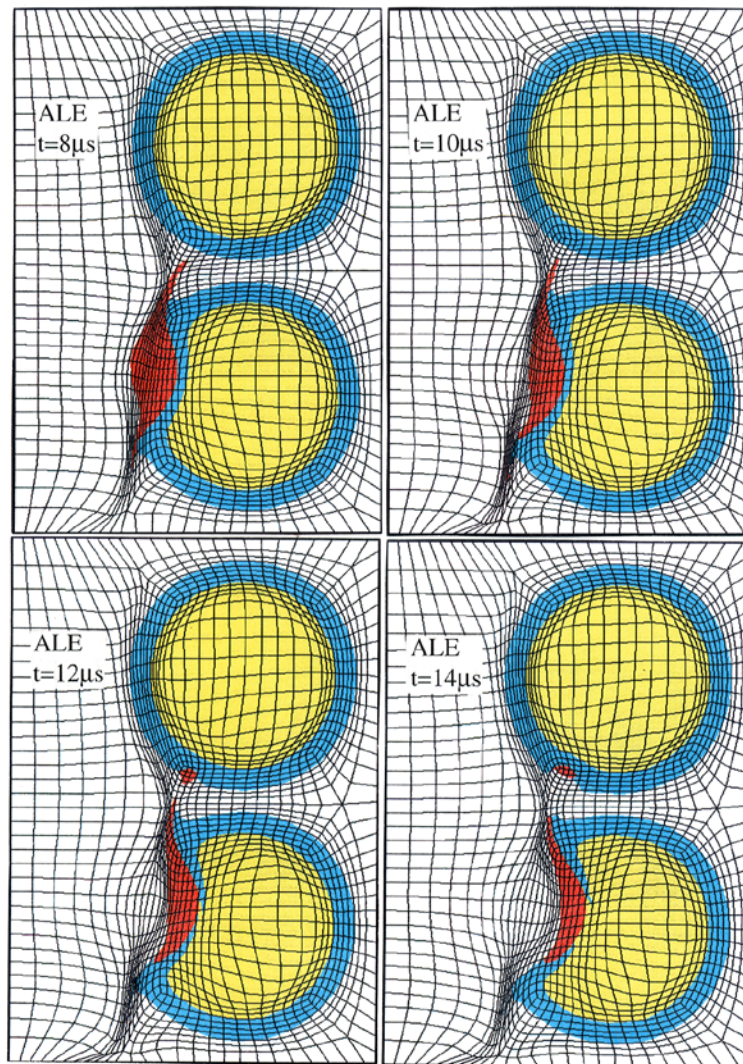


Figure 12: Symmetry plane cross section through an ALE run showing projectile fragmentation.

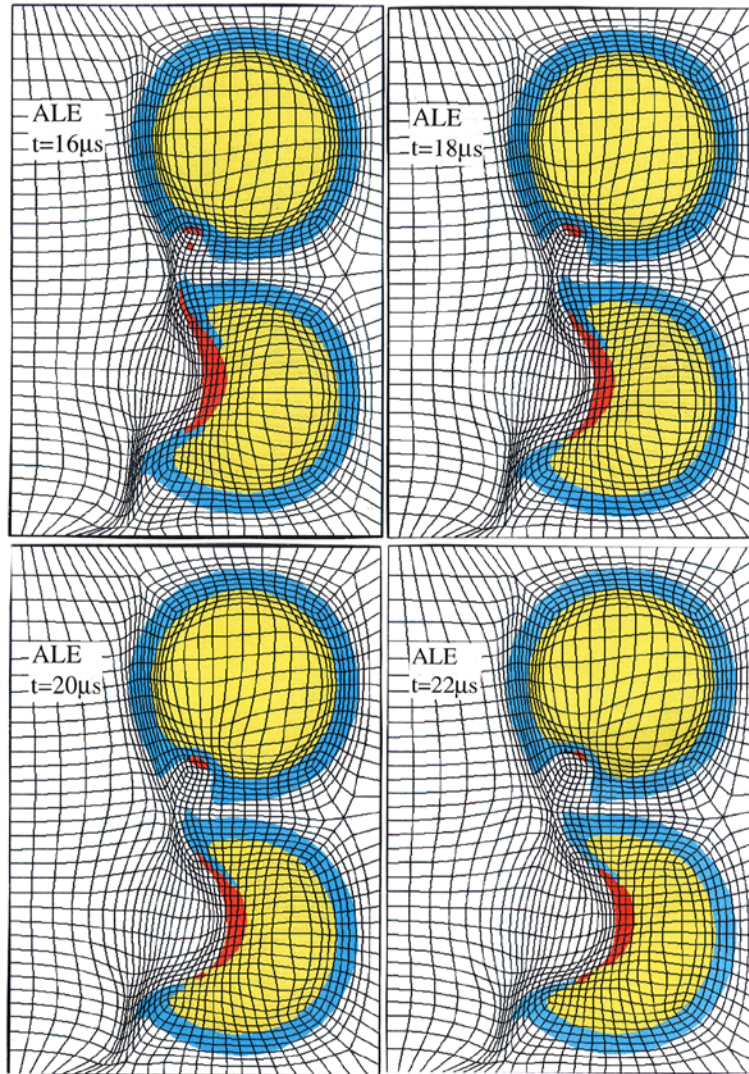


Figure 13: Symmetry plane cross section through an ALE run showing impact of projectile fragments onto adjacent cylinder.

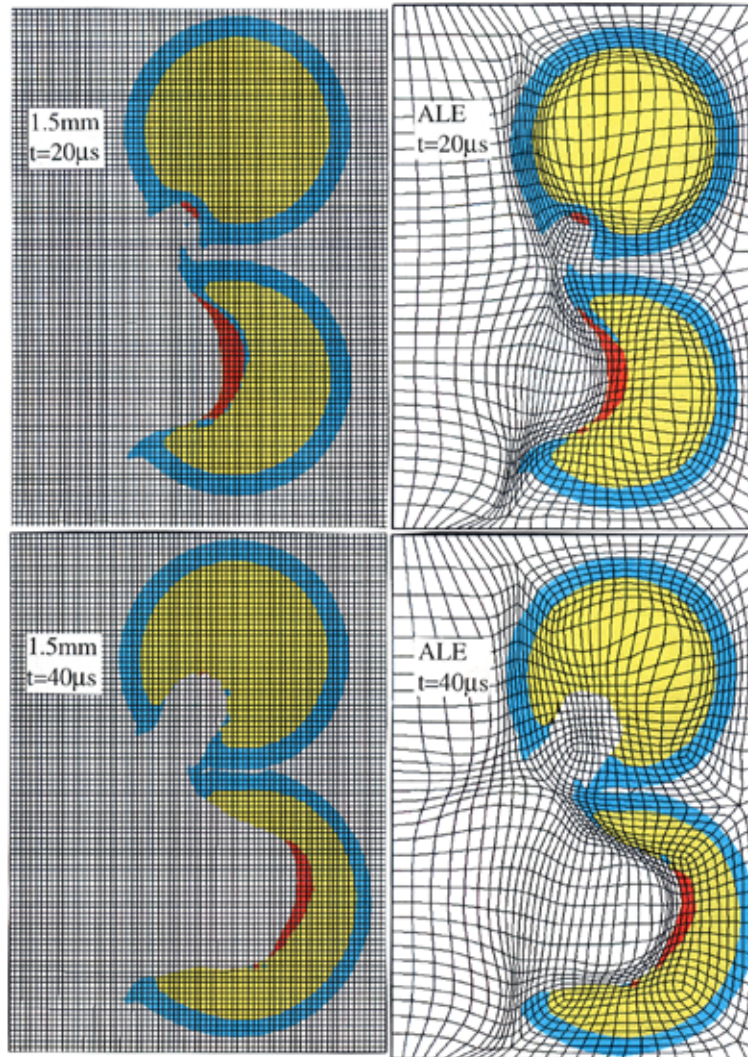


Figure 14: Comparison of symmetry plane cross sections through a finely and uniformly zoned Eulerian run and an ALE run at 20 μsec and 40 μsec .

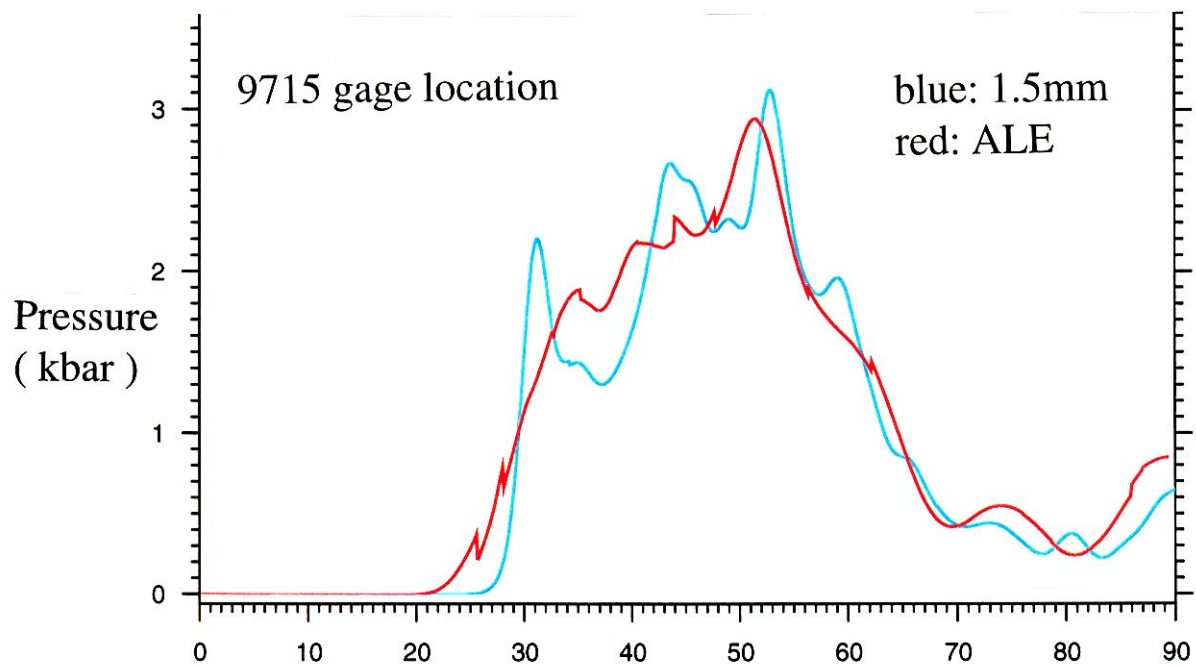
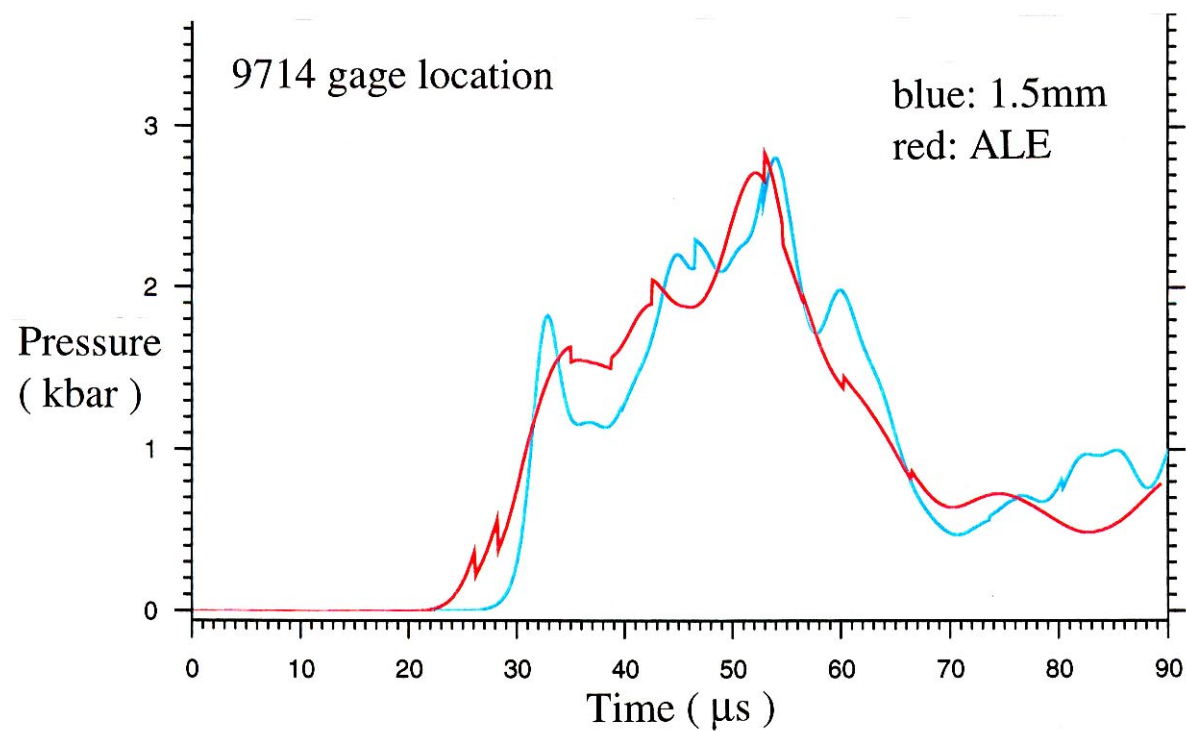


Figure 15: Comparison of pressure profile in adjacent cylinder calculated with a finely and uniformly zoned Eulerian run and an ALE run at locations corresponding to gages in shots 9714 and 9715.

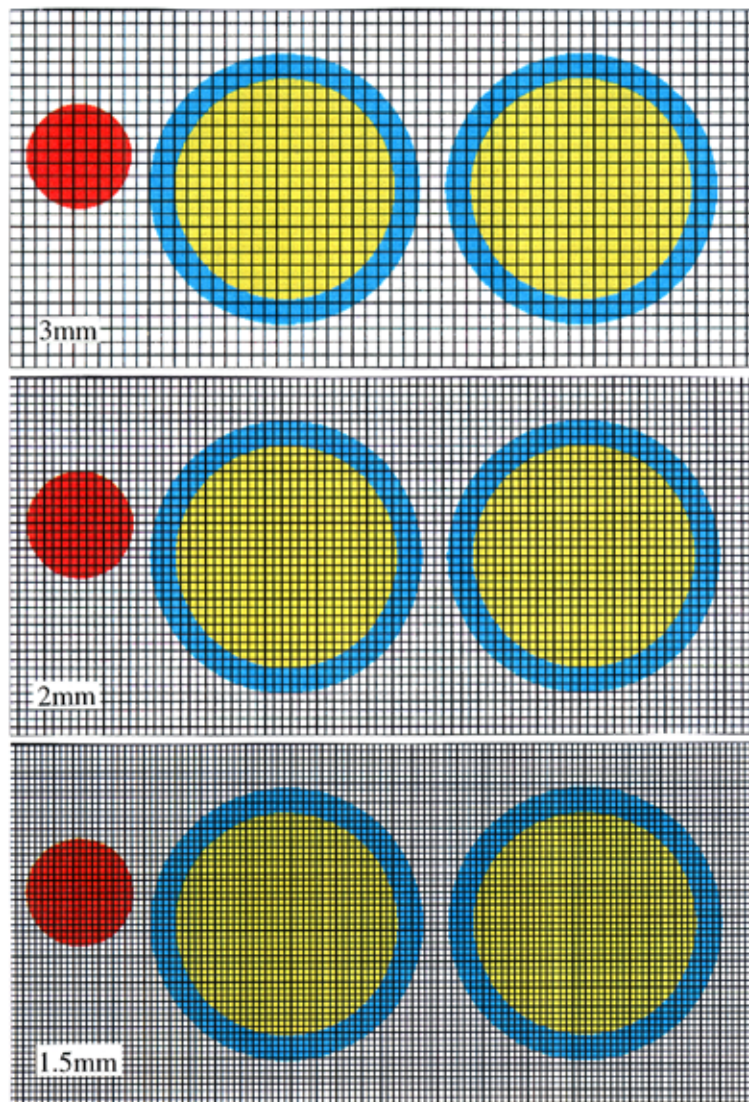


Figure 16: Symmetry plane cross section at problem start through Eulerian runs of different uniform zoning.

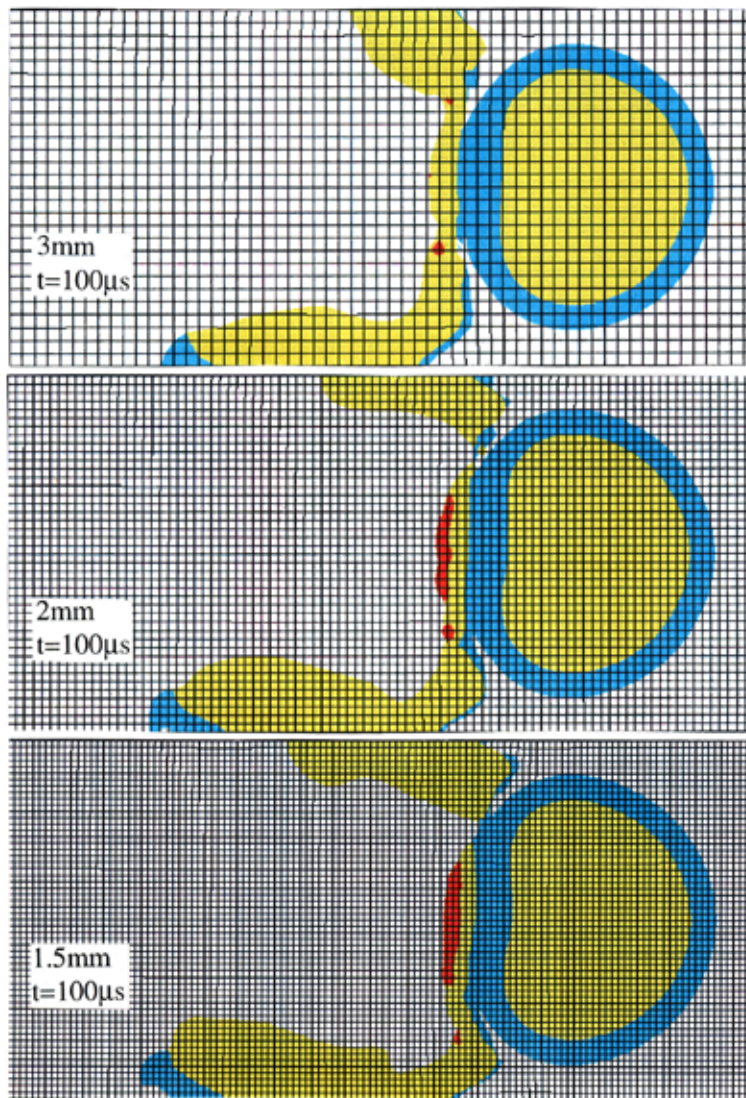


Figure 17: Symmetry plane cross section at 100 μsec through Eulerian runs of different uniform zoning.

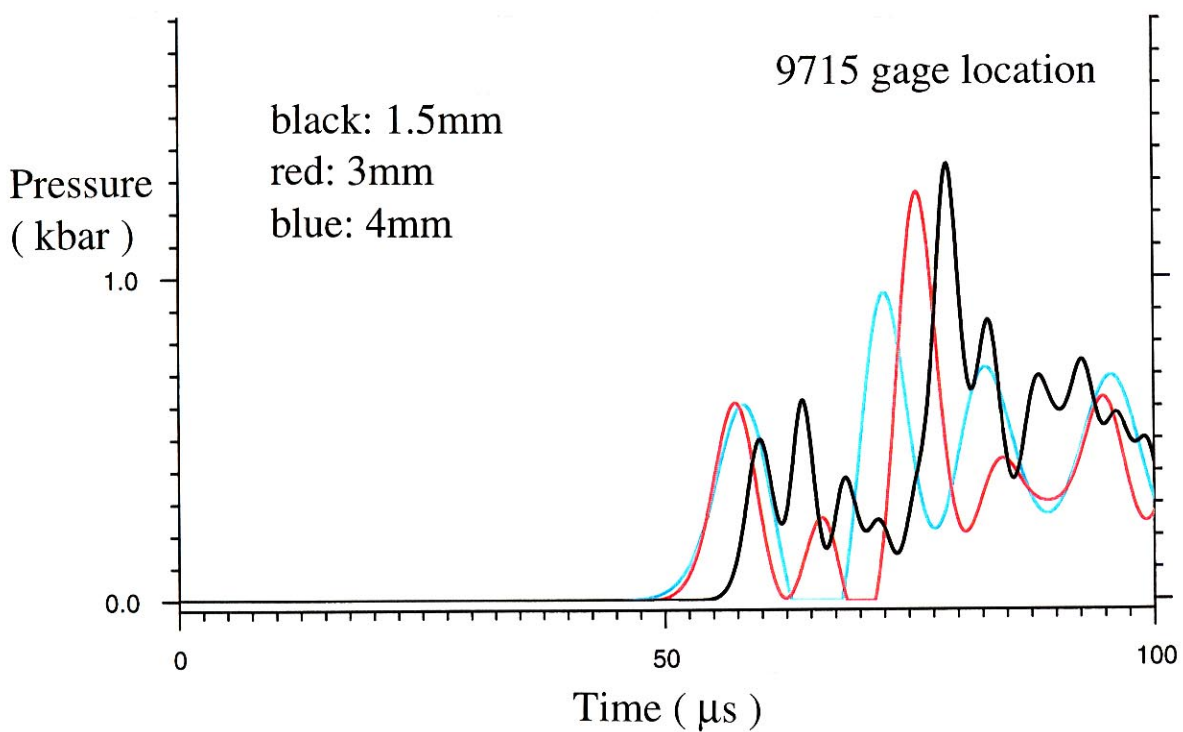
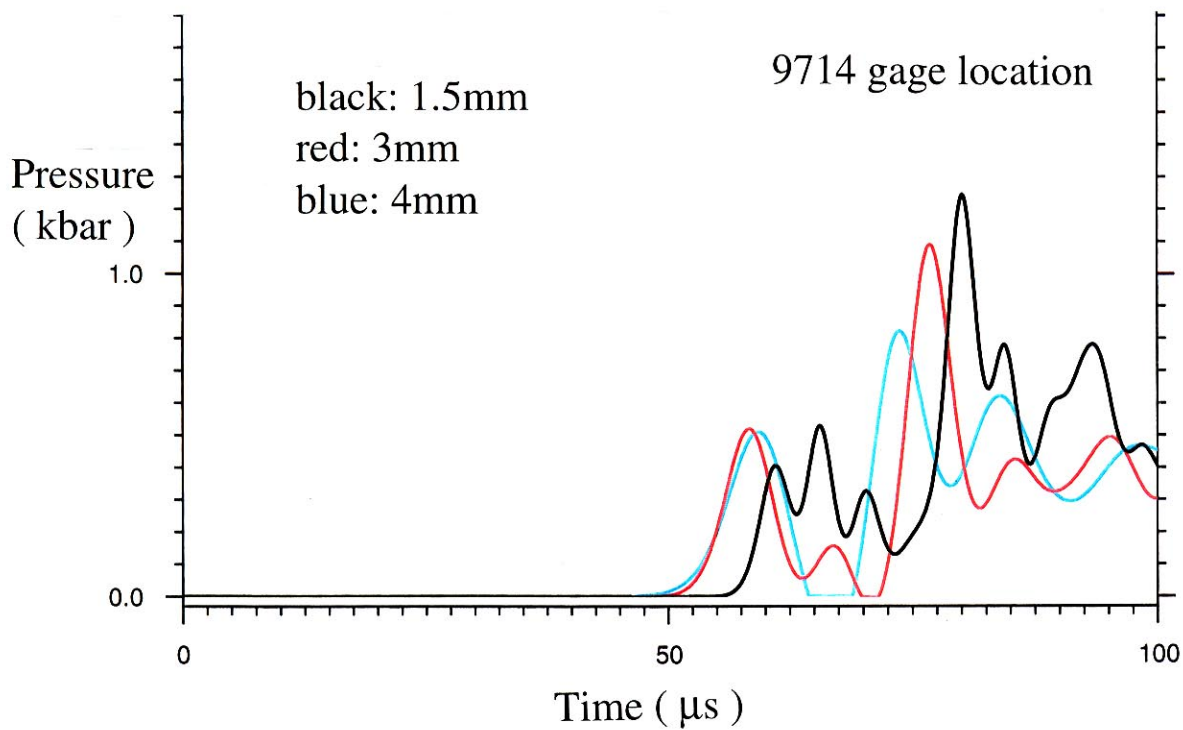


Figure 18: Calculated rear cylinder pressure profiles for Eulerian runs of different uniform zoning at locations corresponding to gages in shots 9714 and 9715.

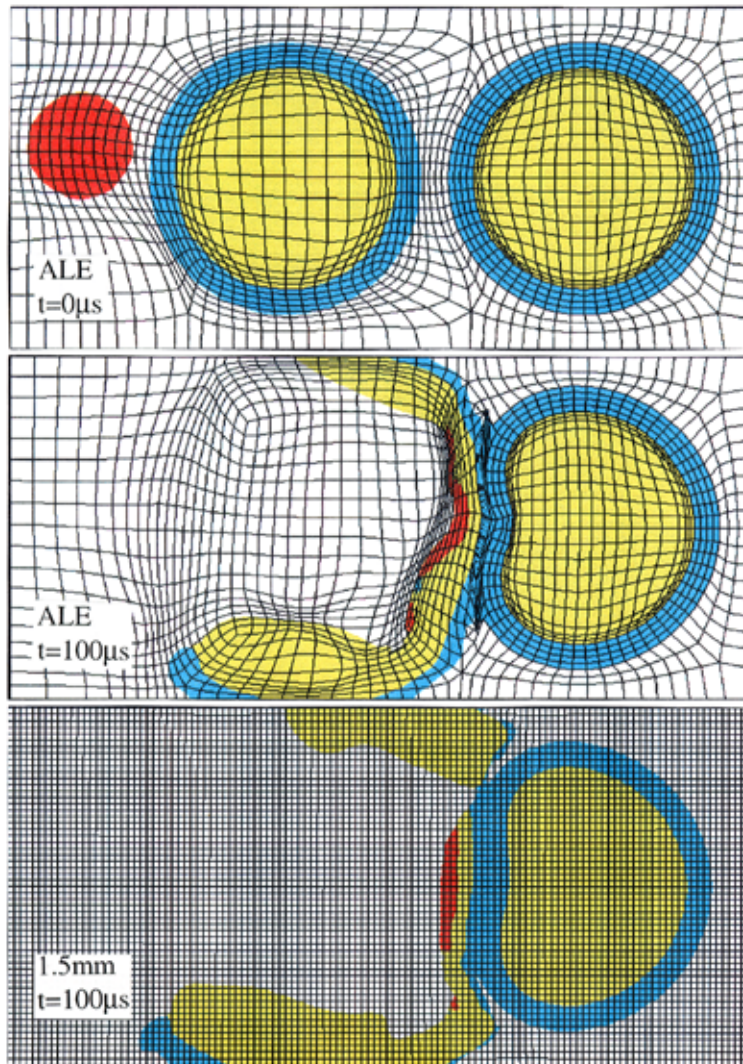


Figure 19: Symmetry plane cross section through an ALE run at $t=0$ and $100\ \mu\text{sec}$ and through a finely and uniformly zoned Eulerian run at $100\ \mu\text{sec}$.

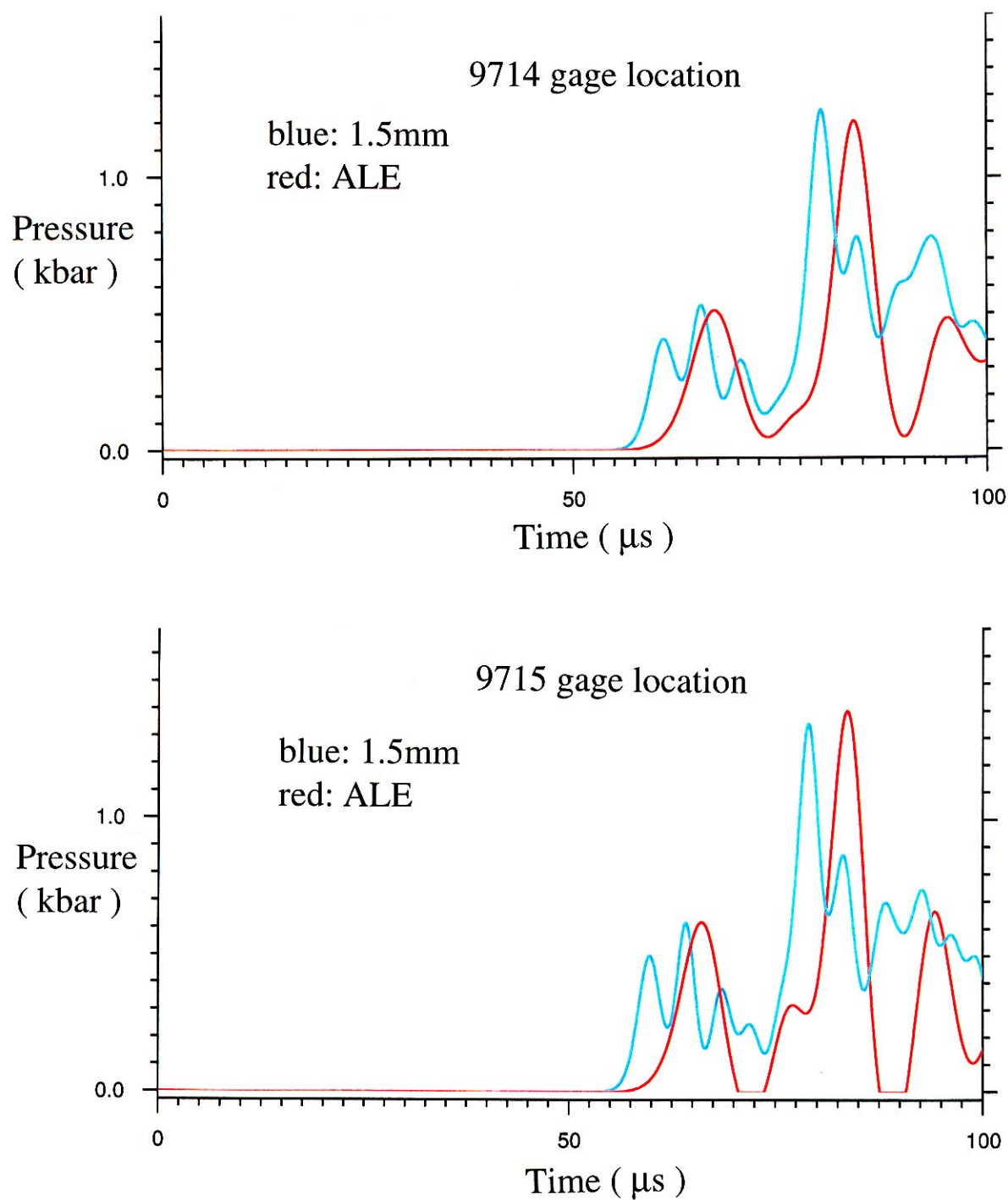


Figure 20: Comparison of measured adjacent cylinder pressure profiles with calculated ones using a finely and uniformly zoned Eulerian run and an ALE run for shots 9714 and 9715.

pressure is calculated in water at the location of the gage. For the adjacent and rear cylinders there is little difference whether the gage location is taken to move with the material or remain fixed in space. For the impacted cylinder it does make a difference and we take the gage location to move with the material. A final comment about timing: the experimental values for 9715 are left unchanged since they match the calculated timing of the pressure rise and reflection off the wall in the impacted cylinder quite well. For 9714, 3 μ sec is added to the recorded values to make the data and the calculations match.

The pressure profiles in the adjacent cylinder for the 1.5mm Eulerian and ALE calculations are compared to data from 9714 and 9715 in Figure 21. The pressure profiles in the rear cylinder for the same calculations are compared to the data in Figure 22. For the adjacent cylinder which calculation represents a better fit to the data is a matter of taste. There is little to choose insofar as the peak amplitude, which we have shown to be very sensitive to zoning, is concerned. The calculated pressures amount to $\sim 2/3$ of the experimental values. While the ALE calculation for 9715 seems to more closely capture the initial timing of pressure rise, the shape of that rise is better captured in the Eulerian calculation. For the rear cylinder the amplitude, which we have shown to be slightly sensitive to zoning is very close for the two calculations and amounts to a little more than half of the experimental value. The timing of the first and largest peaks, which we have shown to be sensitive to zoning, is better matched by the ALE calculation than the 1.5mm Eulerian one. The shape of the peaks for 9714 is better matched by the 1.5mm Eulerian calculation than the ALE one.

Comparison of the calculations with the data shows them to provide similar fits although somewhat poor in both cases. Since we have not established convergence of the calculated pressures with respect to zone size, and do not know the error bar in the measured pressures, we are unable to further investigate the differences between the calculated and measured pressures. Overall we conclude that an ALE calculation with 11 times fewer zones than a uniformly zoned Eulerian calculation provide the same quality fit to the data.

Conclusions

We have compared Eulerian and ALE calculations to each other and to data collected on two experiments. In the experiments the adjacent cylinder was penetrated, but slightly, representing a lethal outcome. The rear cylinder was deformed but not penetrated representing an outcome just short of lethal. Calculations reproduce this behavior, although the calculated pressure profiles have not converged with respect to zone size. Calculations of the pressures in both cylinders show that ALE capability allows 11 times fewer zones to be used compared to a uniformly zoned Eulerian calculation. The ALE calculation also takes about 60% of the cycles required by the equivalent Eulerian one to get to the same time. These advantages are substantial, but it must be realized that they come at a price: special zoning, selected material weights, weighting according to effective plastic strain and Lagrangian treatment of unperforated cylinders. The ALE advantage may well be problem dependent, but it is noteworthy that we find it to be about 11 for outcomes in the vicinity of lethal damage. Whether the ALE advantage is worth the trouble is clearly problem dependent, but it is likely to be the case for a number of problems of interest to the high velocity impact lethality community.

Acknowledgments

Rich Couch of LLNL provided many suggestions in using ALE3D and added tracer point capabilities to the code that facilitated the calculations. Matt Fischer and Sue Webb of LLNL designed the targets used in the experiments. Dick Hayami of the University of Alabama at Huntsville had overall responsibility for the experiments under the guidance of Scott Howard and Mike Cole of the U.S. Army Aviation and Missile Command. Dave Banner, Glenn Pomykal and

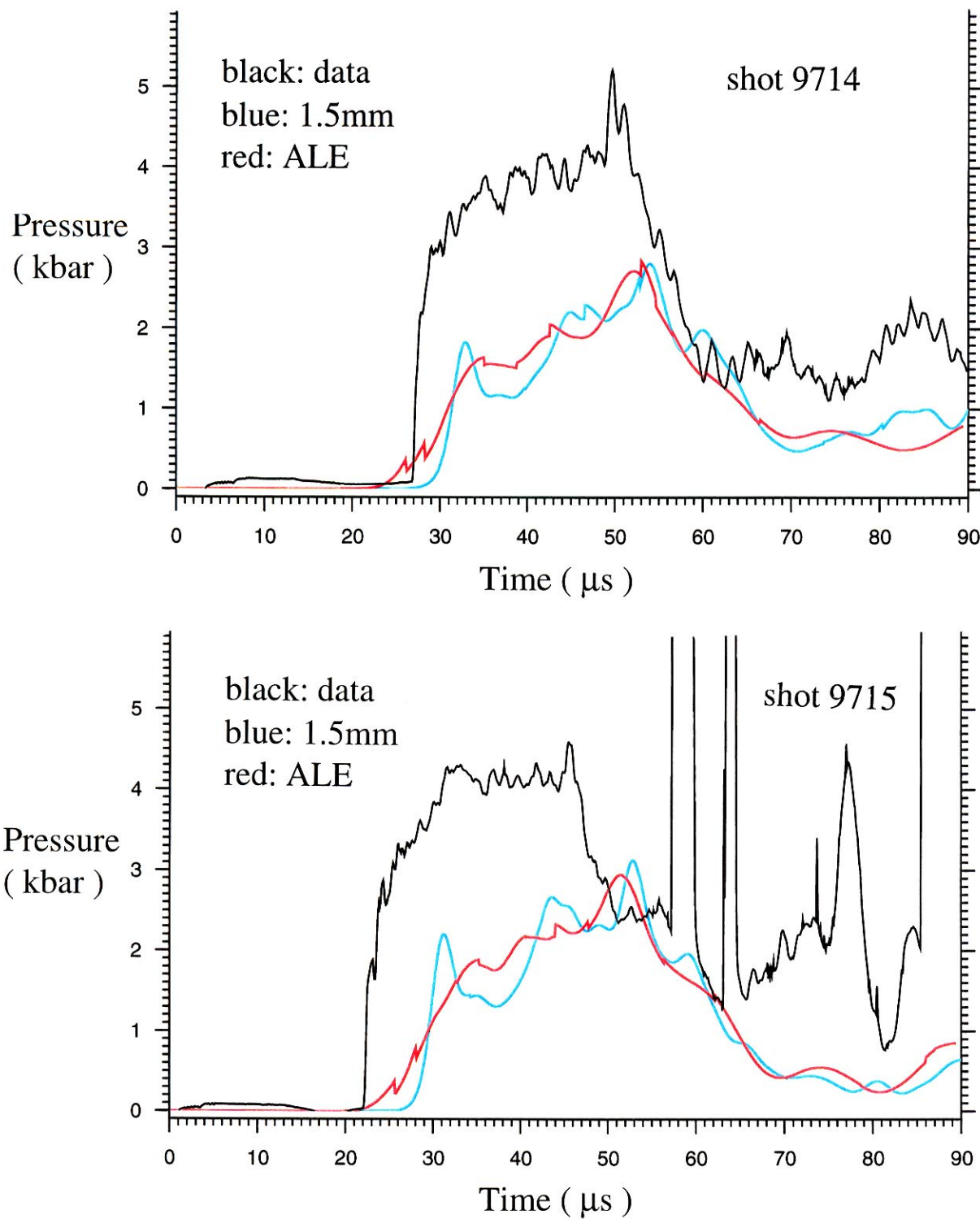


Figure 21: Comparison of measured adjacent cylinder pressure profiles with calculated ones using a finely and uniformly zoned Eulerian run and an ALE run for shots 9714 and 9715.

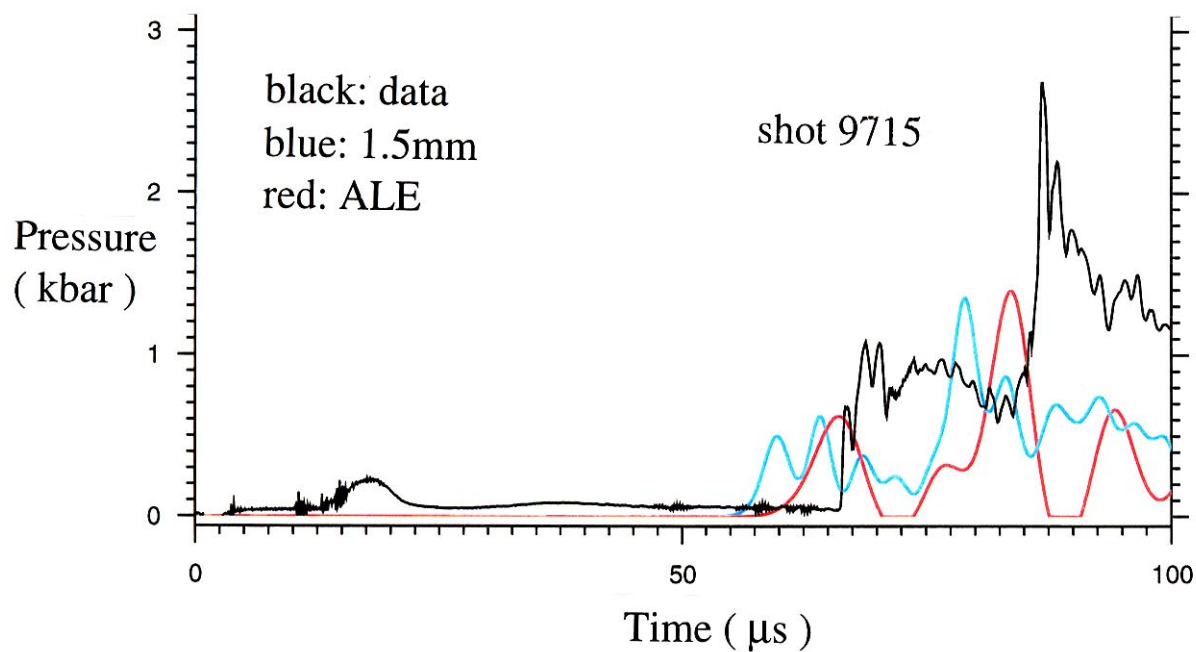
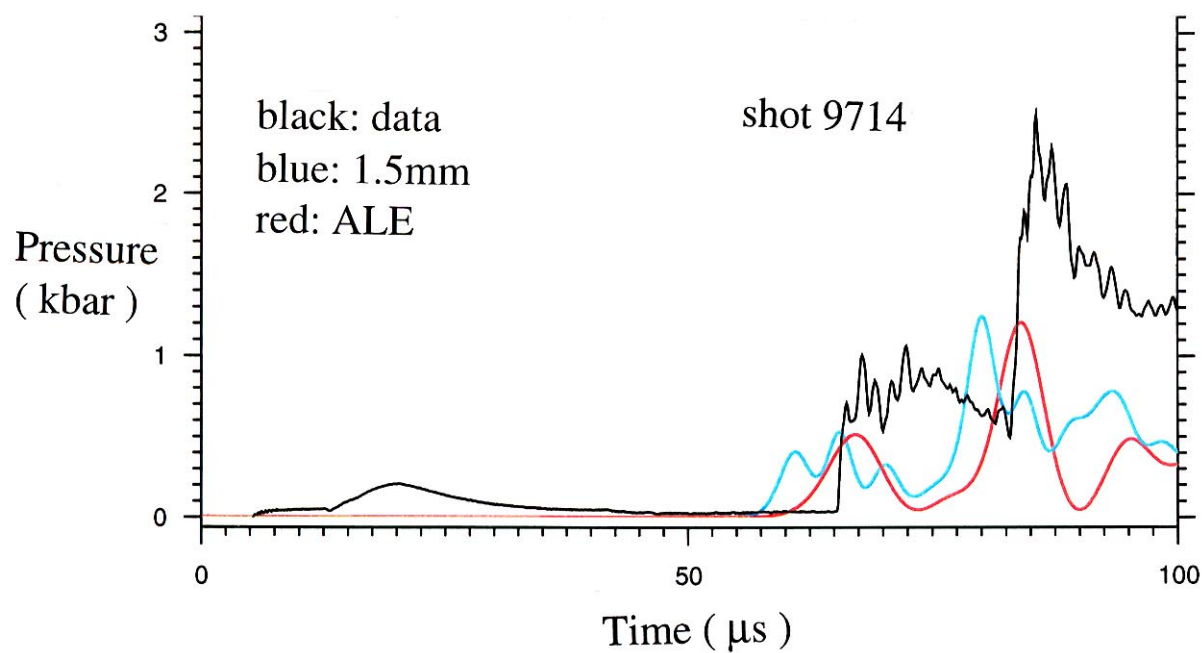


Figure 22: Comparison of measured rear cylinder pressure profiles with calculated ones using a finely and uniformly zoned Eulerian run and an ALE run for shots 9714 and 9715.

Frank Serduke provided suggestions after reading a draft of this document. Work performed by the Lawrence Livermore National Laboratory under the auspices of the Ballistic Missile Defense Organization under MIPR # and under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng.48.

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